Predictive Reliability of Tactical Missiles Using Health Monitoring Data & Probabilistic Engineering Analysis

Stephen A. Marotta

Teng K. Ooi

Abdul J. Kudiya

John A. Gilbert

Houssam A. Toutanji

Integrated Health Monitoring & Prognostics/Diagnostics Systems

- Reliability of the Army's missile stockpile and individual missile shelf life monitored through surveillance and testing program dedication

Army missile and weapon exposure to various long-term environments during storage, transportation, and operation

- Temperature and humidity extremes
- Vibration and shocks
- Corrosive atmospheric conditions

Integrated Health Monitoring

Developed to increase reliability and aid in decision-making for field ops

Prognostics and Diagnostics Systems

- A number of failures due to extreme environmental exposure identified by missile surveillance testing and subsequent failure analysis

Missile Components Diagram

Missile Systems

- **Electrical & Electronic Devices**
  - Microelectronic Devices
  - Discrete Semi-Conductor Devices
  - Electronic Vacuum Tubes
  - Resistors
  - Capacitors
  - Inductive Devices
  - Crystals
  - Miscellaneous Electronic Devices
  - Connectors & Connections
  - Printed Wiring Boards
  - Batteries
- **Electro-Mechanical Devices**
  - Gyros
  - Accelerometers
  - Switches
  - Relays
  - Electromechanical Rotating Devices
  - Miscellaneous Electromechanical Devices
- **Hydraulic & Pneumonic Devices**
  - Accumulators
  - Actuators
  - Bearings
  - Compressors
  - Cylinders
  - Filters
  - Fittings/Connections
  - Gaskets
  - O-Rings
  - Pistons
  - Pumps
  - Regulators
  - Reservoirs
  - Valves
- **Ordnance Devices**
  - Solid Propellant Motors
  - Igniters and Safe & Arm Devices
  - Solid Propellant Gas Generators
  - Miscellaneous Ordnance Devices
- **Optical & Electro-Optical Devices**
  - Seeker Components
  - Fiber Optics
  - Laser Diodes

Categorize Missile Components to Systematically Address Fault Areas

Generic Missile Failure Modes due to Environmental Exposure

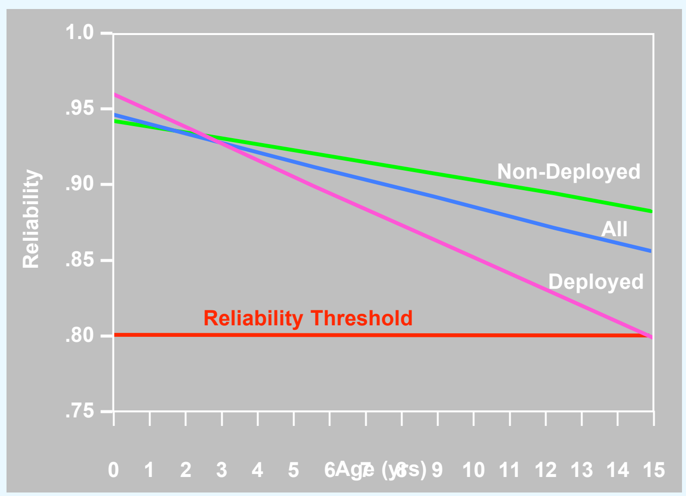
Temperature	Humidity	Shock	Corrosion
• Failure of Electronics Assemblies • Cracks in Packaging and Seals • Failure in Guidance Components – Gyros – Accelerometers • Propellant Grain Cracking • Liner Unbond • Voids and Porosity in Propellant • Case Strength Degradation	• Failure of Electronics Assemblies • Swelling of Packaging • Failure in Guidance Components • Degradation of Ballistic Properties • Degradation of Composite Case • Degradation of O-rings • Degradation of Propellant Properties • Gyros • Accelerometers	• Case Damage • Liner Unbond • Propellant Cracking • Material Fatigue Due to Vibration • Loosening of Components	• Failure of Solder Joints • Corrosion of Metallic Components • Stress Corrosion Cracking at Interconnect/ Bends in Electronic Assemblies • Corrosion of Actuators and Bearings • Corrosion of Contacts • Failure in Squib Wires

Environmental Degradation Drives Field Failures

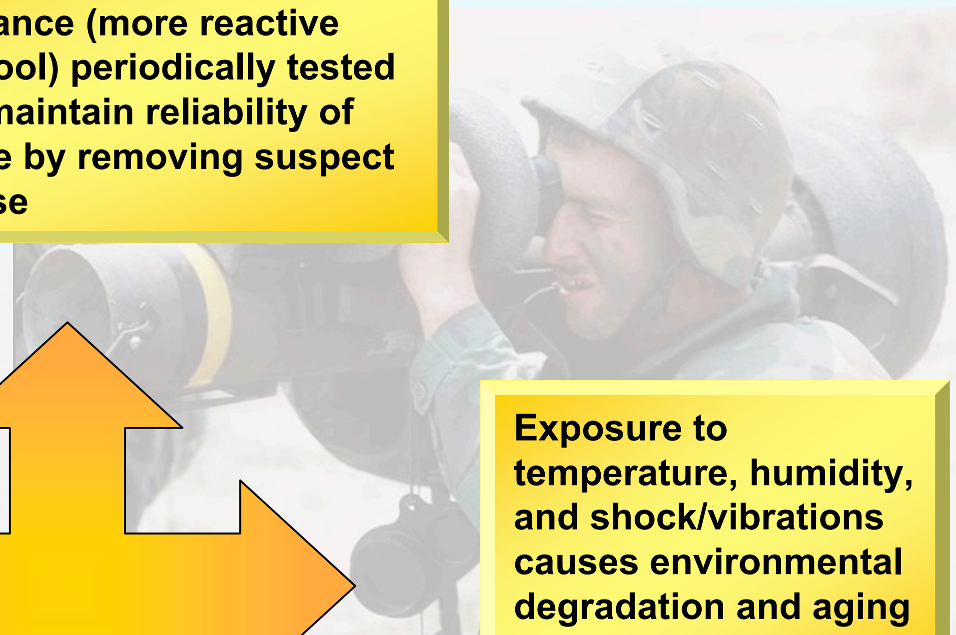
- Shock/Vibration
- Humidity, Rain, Water Immersion
- Sand and Dust
- Electromagnetic Effects
- Low Temperature/Ice
- High Temperature/Solar Radiation

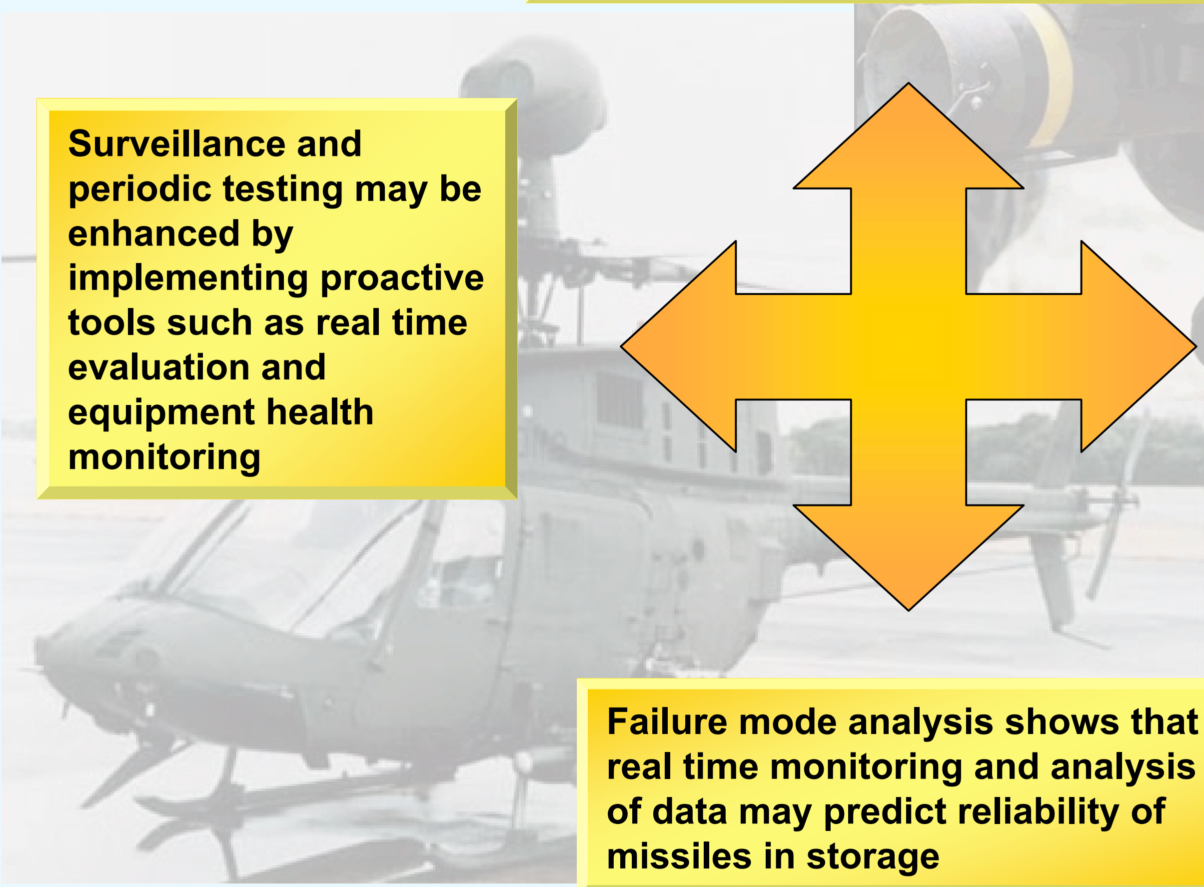






Surveillance Program is a Reactive Tool





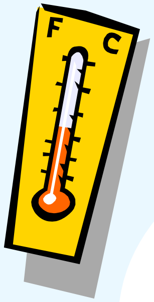
Current surveillance (more reactive than proactive tool) periodically tested by US Army to maintain reliability of missile stockpile by removing suspect assets before use

Surveillance and periodic testing may be enhanced by implementing proactive tools such as real time evaluation and equipment health monitoring

Exposure to temperature, humidity, and shock/vibrations causes environmental degradation and aging effects

Failure mode analysis shows that real time monitoring and analysis of data may predict reliability of missiles in storage

Remote Readiness Assets Prognostics and Diagnostic System (RRAPDS)



- RRAPDS utilizes temperature, humidity, and shock sensors to monitor weapon system environment
- Temperature, humidity, shock, and corrosion can be measured real time with an integrated health monitoring system
- Utilizes Prognostics and Diagnostics Models to determine health, reliability, and service life of weapon systems
- Prognostics and Diagnostics Models in the process of development using probabilistic engineering approach
- US Army has designed a system to monitor missile storage and transportation environments on real time basis

RRAPDS

What *Is* Health Monitoring?

Remote Readiness Asset Prognostics/Diagnostics Systems (RRAPDS)

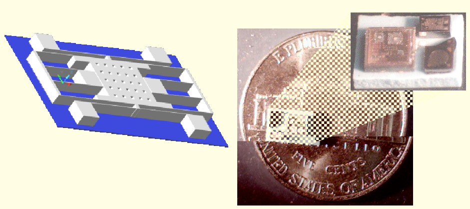
Focus On:

- Monitor/Record Environmental Exposure
- Long Term Storage – 10+ Years
- Understand Impact to the Weapon
- Leverage Existing Infrastructure
- Maintenance Free

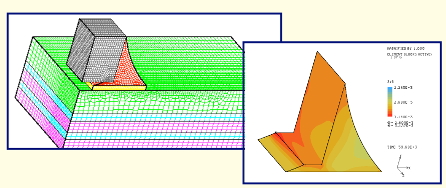
Wireless Interrogator Operated by Ammo/Missile Quality Inspectors

Low Cost Environmental Monitoring Instrumentation Integrated into Each Weapon

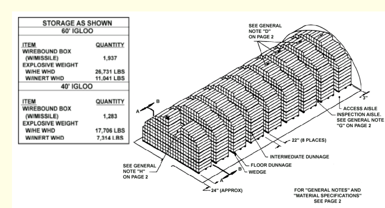
MEMS Sensors



Prognostics Models



Advanced RF Protocols



Prognostic/Diagnostic Models

Diagnostic and Prognostic models being developed to translate RRAPDS data to assess the reliability of weapon systems and use it as a decision making tool for field

Models compute degradation in material properties as a result of exposure to thermal and humidity cycling, shock and vibration, and/or corrosive environment

Degraded material properties used in finite element method or similar technique to evaluate induced internal stresses and predict safety factors

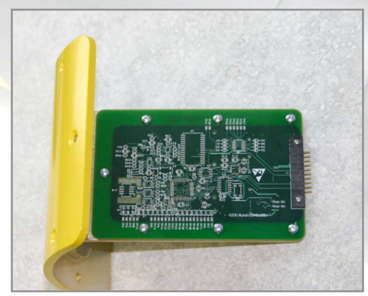
Material properties data determined using sensor information correlated with chemical kinetics or age-related relationships to determine change in modulus, strain energy, or similar property

Probabilistic Approach to Prognostics/Diagnostic Models

- A sound approach to modeling for prognostic or diagnostic analysis of the weapon system will be based on probabilistic engineering approach
- Probabilistic approach will attempt to quantify variability in health monitoring data and modeling uncertainties and forecast the true failure frequency for decision making purposes
- All analyses require the statistical analysis of all the input data to the failure function

Methods of analyzing failure modes (probabilistic engineering)

- Probabilistic engineering evaluation using strength and stress interference
- Probabilistic evaluation of cumulative damage function
- Prediction of component life based on Weibull analysis

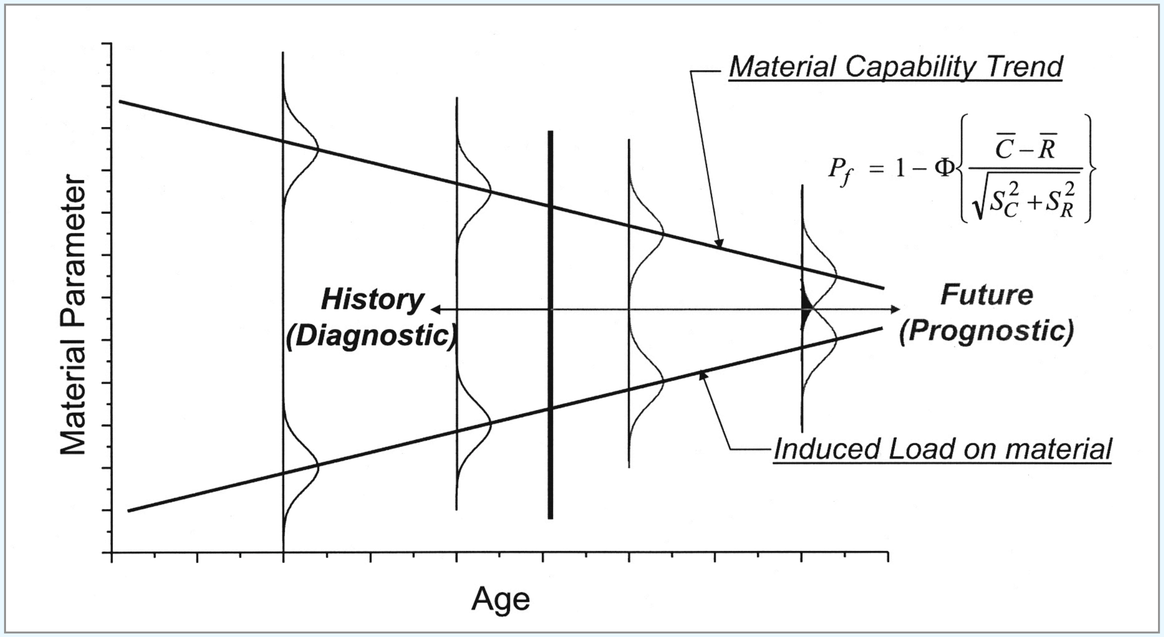
Probabilistic Engineering Models

Stress and Strength Interference	Cumulative Damage Model	Weibull Service Life Predictions
Diagnostic: • Determine Current Reliability of the Structural Components – Propellant – Liner – Case/Canister	***Prognostics/Diagnostics:*** • Fatigue Related Failures • Fracture Mechanics – Crack Propagation in Propellant – Unbonds in Liners – Thermal and Humidity Cycling Effects on Electrical Components • Corrosion Related Failure Modes of Missile Components	***Prognostics/Diagnostics:*** • Age Related Failures of Electrical and Electronics Components • Service Life Predictions – Thermal Batteries – Gas Generators – Guidance Components

Stress & Strength Approach

- In this approach, the material capability (C) and the induced load distributions (R) are used to compute the probability of failure at a point in time.

$$P_f = 1 - \phi\left\{\frac{\overline{C} - \overline{R}}{\sqrt{(S_C^2 + S_R^2)}}\right\}$$



Cumulative Damage Function

- The cumulative damage models evaluate the aggregate of small damages within the component due to stress induced by the environmental conditions over a time period

$$D(t) = \int \left(\frac{\sigma(t)}{\sigma_0} \right)^{\beta} dt$$

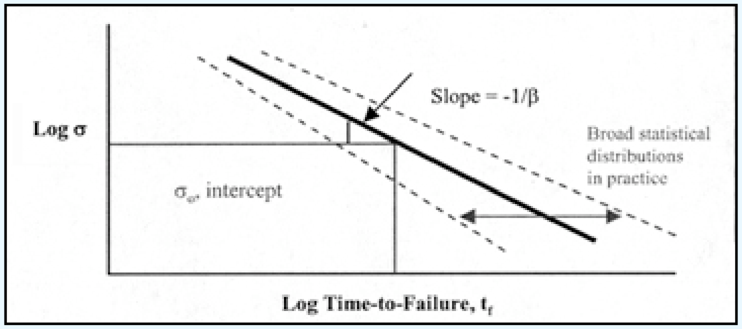
WHERE

T_F = TIME TO FAILURE

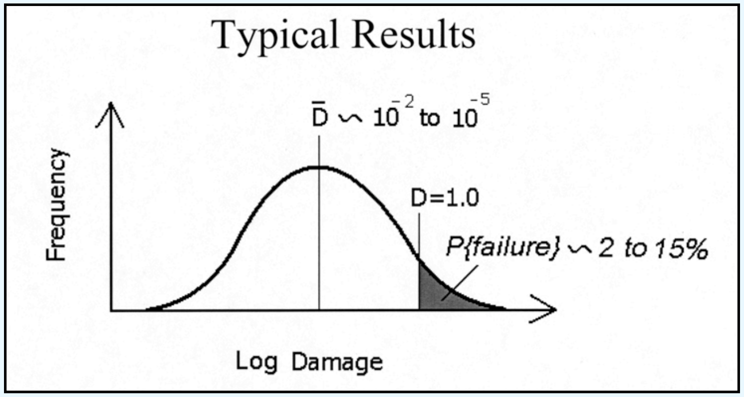
$\sigma(T)$ = IS THE INDUCED STRESS AS A FUNCTION OF TIME
(σ_0)... = MATERIAL STRENGTH
β = POWER LAW EXPONENT SHOW INTERACTION OF STRESS AND STRENGTH PARAMETERS

Probabilistic Evaluation of Cumulative Damage Functions

Time-to-Failure Versus Damage Due to Increased Stress



Failure Probability Distribution Due to Cumulative Damage



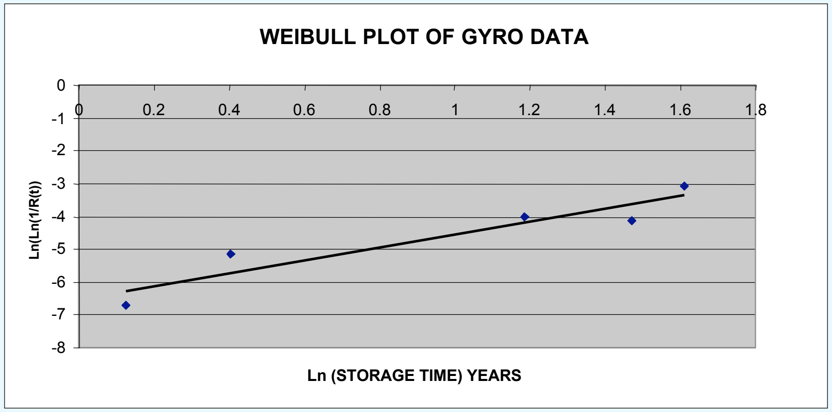
Weibull Probability Analysis

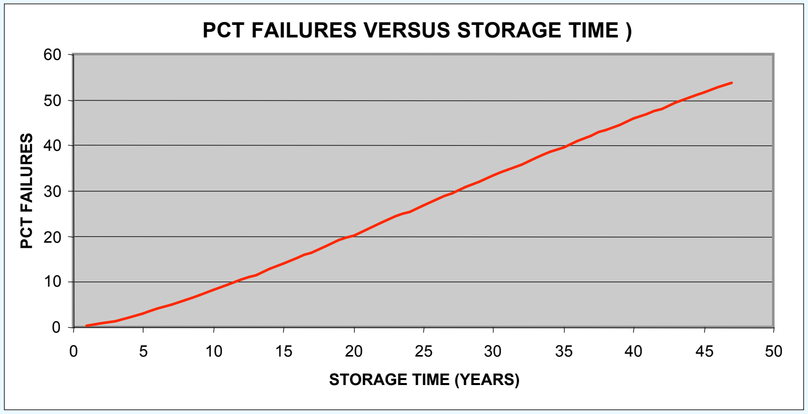
- Weibull Probability Analysis Provides a Useful Tool to Predict Time Dependent Reliability and Component Service Life
- Probability Analysis of Gyros (Example)
  – Degradation of Gyros Performance Due to Degradation in Lubrication Caused by Humidity and Temperature

$$R(t) = 1 - F(t) = e^{-(t/\eta)^{\beta}}$$

Reliability Data on Gyros

Storage Time (years) t	Reliability Success/Total Tested R(t)	ln ln [(1/R(t)])	Ln (t)
1.14	0.9988	-6.718409	0.127061
1.50	0.9942	-5.154005	0.405592
3.27	0.9824	-4.030075	1.185539
4.35	0.9844	-4.150703	1.46978
5.00	0.9548	-3.074563	1.609438





Weibull Service Life Prediction Models

Weibull Reliability Distribution for a compound under stress (σ) is given by:

$$R(\sigma) = \exp\left[-\frac{\sigma}{\sigma_o}\right]^{\beta}$$

From the fracture mechanics model, the material fracture toughness at a given stress level and critical flaw size is given by: $K_{IC} = Y\sigma\sqrt{a_c}$

The final Weibul reliability model for crack propagation as a function of time is shown as:

$$R(t) = \exp\left[\frac{Ct^{1/(n-2)}\sigma^{n/(n-2)}}{\sigma_o}\right]^{\beta}$$

and C is given by $C = \left[\frac{A(n-2)}{2K_{IC}^{2-n}}\right]^{1/(n-2)}$

σ (t) = f (temperature, humidity)

Summary & Conclusions

- U.S. Army Integrated Health Monitoring System combined with Prognostic and Diagnostic Analysis will increase reliability and service life of the weapon systems.
- Probabilistic methods in the diagnostics and prognostics analysis provide a realistic reliability assessment for decisions making purposes.
- Probabilistic models are used to quantify uncertainty in the model and input parameters and provide statistical distribution of the output response.